
CARS Temperature and Species Measurements For Air Vehicle Propulsion Systems

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ABSTRACT

The coherent anti-Stokes Raman spectroscopy (CARS) method has recently been used in the United States and Europe to probe several different types of propulsion systems for air vehicles. At NASA Langley Research Center in the United States, CARS has been used to simultaneously measure temperature and the mole fractions of N_2 , O_2 and H_2 in a supersonic combustor, representative of a scramjet engine. At Wright-Patterson Air Force Base in the United States, CARS has been used to simultaneously measure temperature and mole fractions of N_2 , O_2 and CO_2 , in the exhaust stream of a liquid-fueled, gas-turbine combustor. At ONERA in France and the DLR in Germany researchers have used CARS to measure temperature and species concentrations in cryogenic LOX- H_2 rocket combustion chambers. The primary aim of these measurements has been to provide detailed flowfield information for computational fluid dynamics (CFD) code validation.

1.0 INTRODUCTION

Air vehicle propulsion systems, such as gas turbines, ramjets, scramjets and rockets, are complicated devices that are difficult to model theoretically. The fluid flow through these systems is typically turbulent, three-dimensional, reacting (multi-species), separated, and in some cases, multi-phase. Furthermore, these systems are sometimes tested in facilities in which the test gas is in a state of thermal and/or chemical nonequilibrium. Such flows are very difficult to simulate with state-of-the-art computational fluid dynamics (CFD) codes; these same codes are used to design new engines. Many simplifying assumptions are made in CFD codes in the interest of computational efficiency and also because correct models are not always available, for example turbulence models. Thus, it is critically important to have high-quality experimental data for comparison with these CFD codes to test their validity. A first point of comparison between experimental data and theoretical models is usually performed with conventional wall pressure or thrust measurements. But when disagreements between theory and experiment occur, detailed flowfield data can explain the discrepancy and point towards improving the theoretical models.

Many quantitative flowfield measurement techniques have been developed to study combustion. These are described in detail in Reference 1. Here we briefly overview a few of these methods. Rayleigh scattering can be used to measure temperature, density and gas velocity in high-speed flows. However, in combustion flows, the composition is not generally known, which limits the accuracy that the temperature and density can be determined with this method. Furthermore, composition information is relatively more important than density and velocity for understanding combustions flows. Laser induced fluorescence (LIF) is a method that can provide both temperature and composition information. LIF typically measures a single species, such as nitric oxide (NO), the hydroxyl (OH) radical, or fuel-tracer acetone. Unfortunately, large uncertainties in the collisional environment in combustion flows complicate quantitative measurement of species concentration with LIF. Experiments using LIF to measure temperature and multiple species compositions are very rare, owing to the cost and complexity of the required hardware. Both Rayleigh and LIF have the advantage that they can be performed in an imaging mode in combustions flows, thereby providing useful information about instantaneous flow structures. Raman scattering can provide instantaneous and simultaneous measurement of temperature and multiple species concentrations at a single point in the flow. But large light collection angles and very high-powered lasers are required: both of these limit the application of Raman scattering for practical propulsion devices. The coherent anti-Stokes Raman spectroscopy (CARS) technique is based on Raman spectroscopy and therefore allows simultaneous measurement of temperature and many of the major species present in combustion flows. Unlike Raman scattering, CARS produces a coherent (laser-like) signal beam. Thus, it requires only small windows or windowed slots and the laser energies used do not damage these windows. CARS is a relatively well-understood measurement technique that has been used successfully in many combustion environments. Thus, CARS is a suitable probe for ground-based testing of practical air vehicle propulsion systems.

CARS is a nonlinear optical measurement technique that has been developed for making quantitative measurements in combustion environments for over 30 years.[1] In its simplest form, the CARS process involves crossing three laser beams in a gas. The beams interact with the gas to produce a fourth beam that is detected and analyzed. The spectrum of this beam contains information about the temperature, and composition of the gas. CARS can measure these properties with fast time resolution (10 ns) and good spatial precision (0.2 mm x 0.2 mm x 2.0 mm, typically). The CARS method can be adapted to a variety of measurement applications according to the flow composition and the measurement requirements. In this paper, four different CARS approaches have been used to probe four different air vehicle propulsion systems. The CARS method is first described in more detail and differences in the various experiments are identified.

Then, each experiment is briefly summarized including highlights of the major results of each study.

2.0 CARS APPROACHES

2.1 Overview of the CARS Measurement Technique

In the most commonly-used CARS approach, two collimated green laser beams derived from the same Nd:YAG laser form the *pump* beams as shown in Figure 1(a). One collimated red beam from an Nd:YAG-pumped dye laser forms the *Stokes* beam. The pump and Stokes beams are directed through a spherical lens that crosses and focuses the three beams at a point as shown in the figure. A Raman interaction between these three laser beams and the gas present in the beam-crossing volume generates a blue signal beam, known as the *anti-Stokes* beam. If the Stokes laser has a broadband spectrum then the anti-Stokes beam is also broadband. In this case, the anti-Stokes beam can be dispersed with a spectrometer onto a CCD camera and the Raman spectrum is acquired in a single laser pulse. This method is known as *broadband CARS*. [1] Commonly, the frequency difference between the green and red beams is chosen to probe Raman transitions in N_2 . Alternately, a different laser dye can be used in the Stokes laser to probe other molecules, such as H_2 and H_2O . An example of the N_2 CARS spectrum is shown in Figure 2. The N_2 spectrum contains both rotational and vibrational spectral features, each having different ground-state energies. The shape of this spectrum is very sensitive to the gas temperature since the distribution of molecules among these states is dictated by the gas temperature. At low temperatures, the higher energy level states (to the left of the figure) are unpopulated whereas at high temperatures these states are populated. These population distributions determine the shape of the spectrum, so one can determine temperature by measuring this spectrum. Additionally, the magnitude of the anti-Stokes signal from N_2 is related to the mole fraction of N_2 , though additional information is required to precisely determine N_2 mole fraction from such a spectrum.

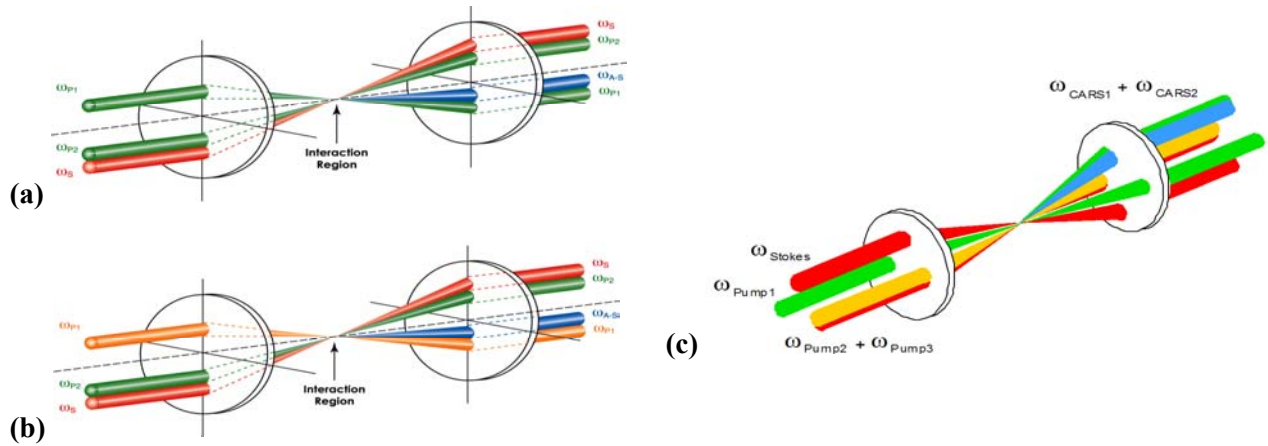


Figure 1: CARS approaches: (a) broadband CARS, for probing N_2 [Ref. 1], or H_2 and H_2O [Refs. 4 and 8], (b) dual-pump CARS, for probing N_2 - O_2 - H_2 [Ref. 2] or N_2 - CO_2 [Ref. 3], (c) dual-pump dual-broadband CARS for probing N_2 - CO_2 and N_2 - O_2 [Ref. 3]. The planar BOXCARS phase matching is illustrated in (a) and (b) whereas (c) shows the folded BOXCARS geometry.

2.2 Description of CARS Approaches

Several variations have been developed that have enhanced the basic broadband-CARS method, depending on the application. In H_2 -air combustion systems, it is useful to measure temperature, N_2 , O_2 and H_2 . [2]. On the other hand, in hydrocarbon-air combustion systems, carbon dioxide is of primary interest so it is desirable to simultaneously measure temperature, N_2 , O_2 , and CO_2 . [3] Similarly, in H_2 - O_2 combustion applications, a system that measures temperature, H_2 and H_2O is a sensible choice. [4] These different CARS approaches are applicable in different flow environments. These systems are described in further detail below.

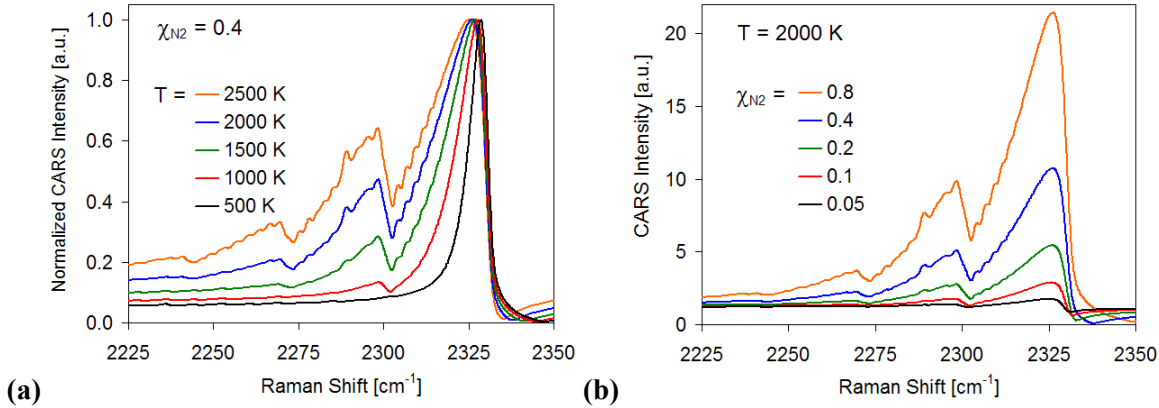


Figure 2: N_2 CARS Spectra calculated from the Sandia CARSFIT code [12], illustrating (a) temperature sensitivity, while N_2 mole fraction is held constant, and (b) N_2 concentration sensitivity, while temperature is held constant. Calculated at 1 atmosphere.

2.2.1 N_2 - O_2 - H_2 Dual-Pump CARS at NASA Langley Research Center, USA

The *dual-pump* CARS method had been developed by Robert Lucht and coworkers. [5] It is a variation on the broadband CARS scheme described above in that one of the green pump beams is replaced by a narrowband, tunable, pump beam. The color of this laser is chosen so that the frequency difference between this laser and the broadband Stokes laser corresponds to the Raman shift of one molecule of interest, such as O_2 . As before, the color of the Stokes laser is chosen so that the frequency difference between it and the first (green) pump beam corresponds to the Raman resonance in the other molecule of interest, e.g. N_2 . This technique has several merits. Most importantly, the two anti-Stokes spectra resulting from the two different species occur at nearly the same wavelength, despite having vastly different Raman shifts, so that they appear side by side at the exit of a spectrometer and can be acquired by a single CCD camera. This simplifies the setup compared to other approaches that require multiple cameras and spectrometers. Another merit is that the same three lasers are involved in generating the two signal beams. Thus, there is a very high degree of correlation between the relative intensities of the two measured spectra. Consequently, laser-energy measurements and relative detector calibrations (and their resulting uncertainties) are not necessary with this method. Another merit when applying dual-pump N_2 - O_2 CARS to study H_2 combustion is that there are several pure rotational H_2 lines coincident with the N_2 and O_2 spectra. [2] Thus, N_2 , O_2 , and H_2 can simultaneously be measured along with temperature. This is the approach taken at NASA Langley Research Center in Hampton, Virginia to study supersonic combustion. [2] This setup uses a frequency-doubled 532 nm (green) Nd:YAG laser for one pump beam, a 555 nm (yellow) narrowband Nd:YAG-pumped dye laser for the second pump beam and a broadband 607 nm (red) laser for the Stokes beam. The anti-Stokes signal is generated at 491 nm (blue). This

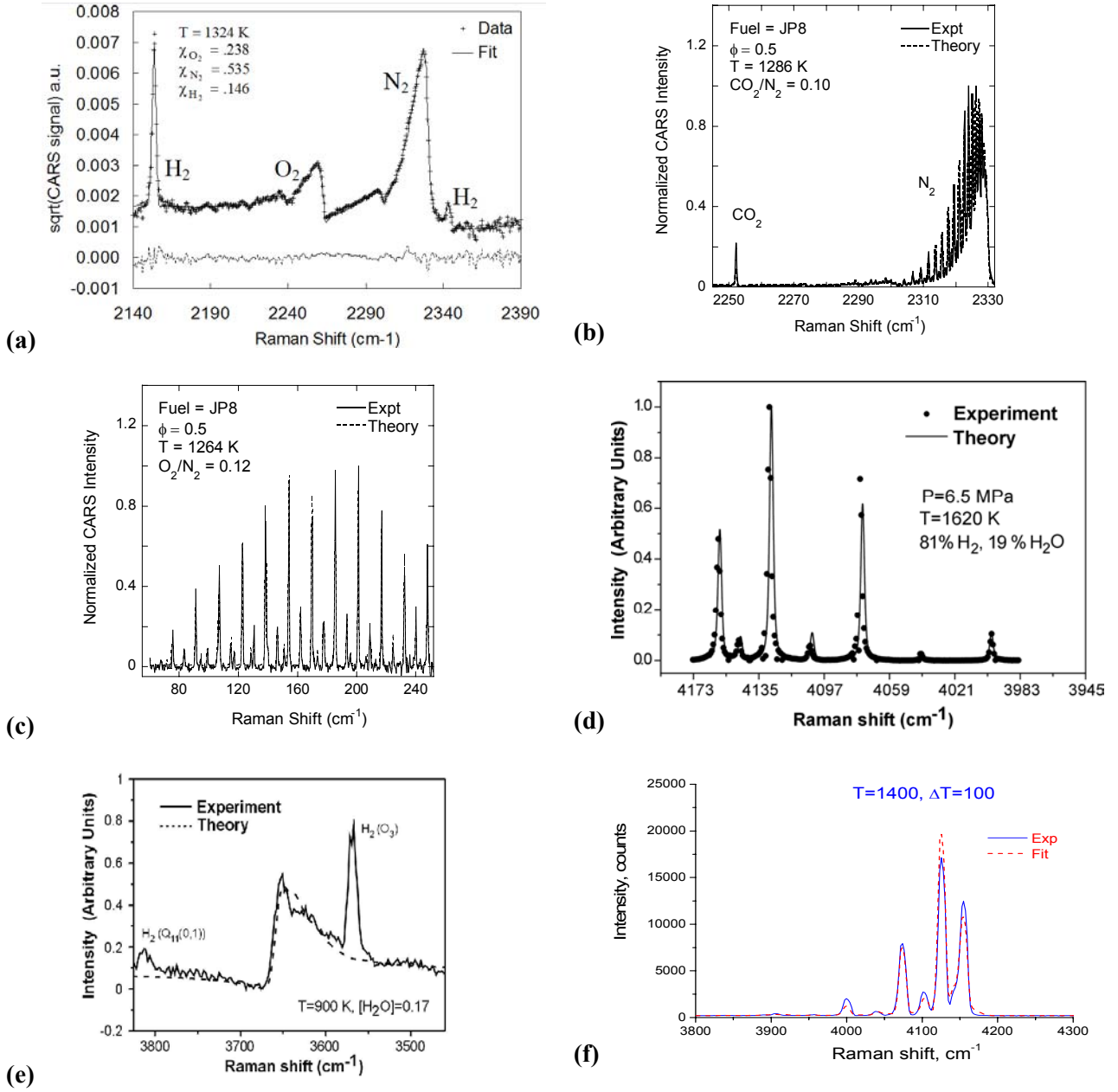


Figure 3: Measured single-shot CARS spectra and fits from: (a) NASA Langley dual-pump N₂-O₂-H₂ CARS, (b) Wright-Patterson Air Force Base dual-pump N₂-CO₂ CARS, (c) Wright-Patterson Air Force Base dual-broadband N₂-O₂ CARS (d) the ONERA broadband H₂ CARS, (e) ONERA broadband H₂O CARS, and (f) H₂ spectra from the DLR broadband H₂-H₂O CARS systems.

arrangement is shown in Figure 1(b). A typical spectrum obtained from this system is shown in Figure 3(a).

2.2.2 N₂-O₂-CO₂ Dual-Pump Dual-Broadband CARS at Wright-Patterson Air Force Base, USA

At Wright-Patterson Air Force Base, *dual-pump dual-broadband CARS* (DPDB-CARS) has been developed and applied for the measurement of temperature and multiple-species mole fractions in laboratory flames and

liquid-fueled combustors of practical interest.[3,6,7] In this approach pure rotational transitions of O_2-N_2 and ro-vibrational transitions of CO_2-N_2 are probed using two narrowband pump beams, a broadband pump beam, and a broadband Stokes beam. The DPDB-CARS system described here can be viewed as a combination of the dual-pump and dual-broadband approaches, the former generating a ro-vibrational CARS signal from the N_2-CO_2 pair and the latter generating a pure rotational CARS signal from the N_2-O_2 pair. This technique permits highly accurate temperature measurements at both low and high temperatures as well as mole-fraction measurements of two molecules with respect to N_2 from each laser shot. The ability to compare temperatures measured from both O_2-N_2 and CO_2-N_2 spectra provides a check on the accuracy and increases the dynamic range of the single-shot temperature measurements. In the combustion zone or the exhaust stream of a real combustor, wide spatial and temporal variation of temperature can occur due to the inherent turbulent nature of the flow field. In the current system the rotational spectra of O_2-N_2 ensure high accuracy at lower temperatures, generally below 1500 K, because a higher percentage of the population resides at lower energy levels under these conditions. The ro-vibrational spectra of CO_2-N_2 ensure high accuracy at elevated temperatures because a higher percentage of the population is transferred to higher energy levels under these conditions. In much the same way as dual-pump CARS described above, each pair of CARS signals is generated over a relatively narrow wavelength region and can be captured with fixed-wavelength detection. This eliminates potential errors arising from wavelength-dependent variations in signal transmission or detector efficiency. The folded BOXCARS geometry employed in these studies is depicted in Figure 1(c). Typical single-shot spectra are shown in Figures 3(b) and 3(c).

2.2.3 CARS System at ONERA, France

The CARS system used at ONERA was developed to perform single-shot temperature measurements in reactive flowfields. The system consists of an optical bench which simultaneously produces the pump and Stokes beams. The pump beam was the frequency-doubled output of a Nd:YAG laser chain composed of a single-mode Q-switched oscillator followed by an amplifier. The laser delivered 140 mJ in 13 ns pulses with a 15 Hz repetition rate. Half of the green energy was used to pump the Stokes dye laser which emits the broadband ω_2 beam. For instance, LDS 698 diluted in ethanol was used to produce the Stokes beam centered at 683 nm with a 200 cm^{-1} bandwidth (FWHM) when exciting H_2 for LOX/ GH_2 combustion studies. The planar BOXCARS configuration was used for the experiment (i.e. the pump beam was split into two parallel beams and one of them was overlapped with the ω_2 beam). The laser beams were then focused in an argon cell where a non-resonant CARS signal was created to monitor the shot-to-shot fluctuations of laser beam energy and of the spectral shape of the Stokes beam. That reference signal was subsequently split off and all laser beams were focused in the combustion chamber using a single 200 mm-focal-length achromat yielding a 1 mm-long and $50\text{ }\mu\text{m}$ -diameter probe volume. Reference and sample H_2 CARS spectra were dispersed using two separate spectrometers. The single-shot CARS H_2 spectrum and the broadband reference were formed in the output plane of the spectrographs and detected by means of intensified photodiode arrays. Typical single-shot spectra for H_2 and H_2O are shown in Figures 3(d) and 3(e), respectively. More complete details of the ONERA CARS system can be found in Reference 4.

2.2.4 CARS System at DLR Lampoldshausen, Germany

The H_2-H_2O CARS system at DLR Lampoldshausen was developed and adopted for applications at high-pressure conditions in a co-operation with the group of V.Smirnov, Department of Optical Spectroscopy of the Russian Academy of Sciences. The CARS set-up is described in detail in Reference 8. The system consists of a frequency-doubled Nd:YAG laser and a modeless dye laser, providing the pump- and Stokes-laser beams in the broadband CARS configuration. The implementation of the modeless dye laser significantly reduces the noise level in the CARS signal.[9] The dye profiles of the Stokes laser is broad enough to simultaneously

probe the H_2 and H_2O molecules. Probing simultaneously ensures a signal from at least one of the species occupying the probe volume depending on relative concentration. For the temperature evaluation from the CARS spectra, a fitting code is applied. This procedure determined the best fit to theoretically calculated spectra and thus obtained gas temperatures. An example of a fit of H_2 -CARS spectra is presented in Figure 3(f). The precision of temperature measurement depends critically on the reliability of line broadening coefficients together with their dependencies on temperature and concentration of collision partners. For the determination of H_2 line broadening coefficients for H_2 - H_2O collisions, CARS spectroscopy experiments were performed in a high-pressure pulsed hydrogen-oxygen burner with variable and controlled pressure [10]. Such a technique provides insight to the turbulent reacting flow and furthermore, information on the partial density of water can be deduced from H_2O -CARS spectra, which is important for the analysis of the H_2 -spectra.

3.0 EXPERIMENTAL RESULTS

3.1 Supersonic Combustion Experiments at NASA Langley Research Center, USA

3.1.1 Experimental Test Hardware and Procedure

Researchers at NASA Langley Research Center needed to acquire detailed flowfield data in supersonic hydrogen-fueled combustors to provide data for comparison with CFD codes used to develop scramjet engines. Such engines were used in the Hyper-X flight program, which had two successful flights in 2004. Test hardware was chosen to be representative of the flow typical in scramjet engines, but the Hyper-X flowpath itself was not investigated in the tests to be described, because it is classified. Instead, an axial fuel-injection configuration was tested.[2] Subsequently a normal-fuel injection case was also tested,[11] but only the axial case is discussed here. The geometry of the axial fuel-injection configuration is shown in Figure 4. The tests were performed in Langley's Direct Connect Supersonic Combustion Test Facility, which is a combustion-heated (hydrogen vitiated) facility. The facility heater was operated at a temperature simulating Mach 7 flight. A converging-diverging nozzle was mounted at the end of the heater, providing Mach 2 flow into the supersonic combustion duct. The duct consisted of two sections: an upstream duct made of copper and a downstream duct made of steel. Unheated hydrogen fuel was injected supersonically at Mach 2.5 at an angle of 30 degrees with respect to the incoming flow in the copper duct. The equivalence ratio is 1. Both copper and steel ducts had a 3-degree divergence angle on the top wall and a horizontal bottom wall. The side walls were parallel to each other. These ducts were equipped with slotted windows on the sides to pass the CARS laser beams. The test hardware was uncooled, so the test time was limited to about 20 seconds per run, with ~15 minutes of cool down time required between runs. Approximately 20 runs could be performed per day. The laser operated at 10 Hz. Thus, approximately 4000 measurement points could be obtained per day.

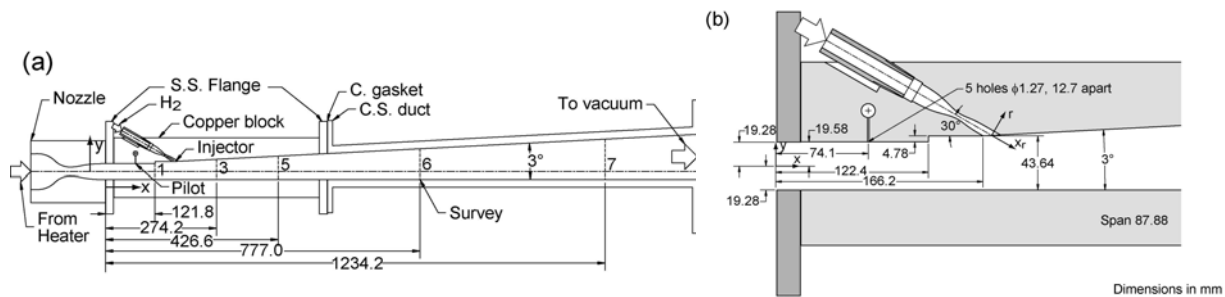


Figure 4: Test Configurations for supersonic combustion test hardware at NASA Langley Research Center: (a) full schematic showing the facility nozzle (far left), copper (left) and steel (right) ducts and (b) close-up of injection region. Seven windowed measurement ports are indicated by numbers in (a). All dimensions are in millimeters.

A periscope system allowed the CARS measurement volume to be moved around in the flow, allowing a single spanwise plane in the flow to be mapped each day. The CARS spectra were analyzed with a NASA-Langley-modified version of the Sandia CARSFIT code.[12] Then, response surfaces were fit to the measured data to produce the resulting temperature, N_2 , O_2 and H_2 mole fraction maps.[13]

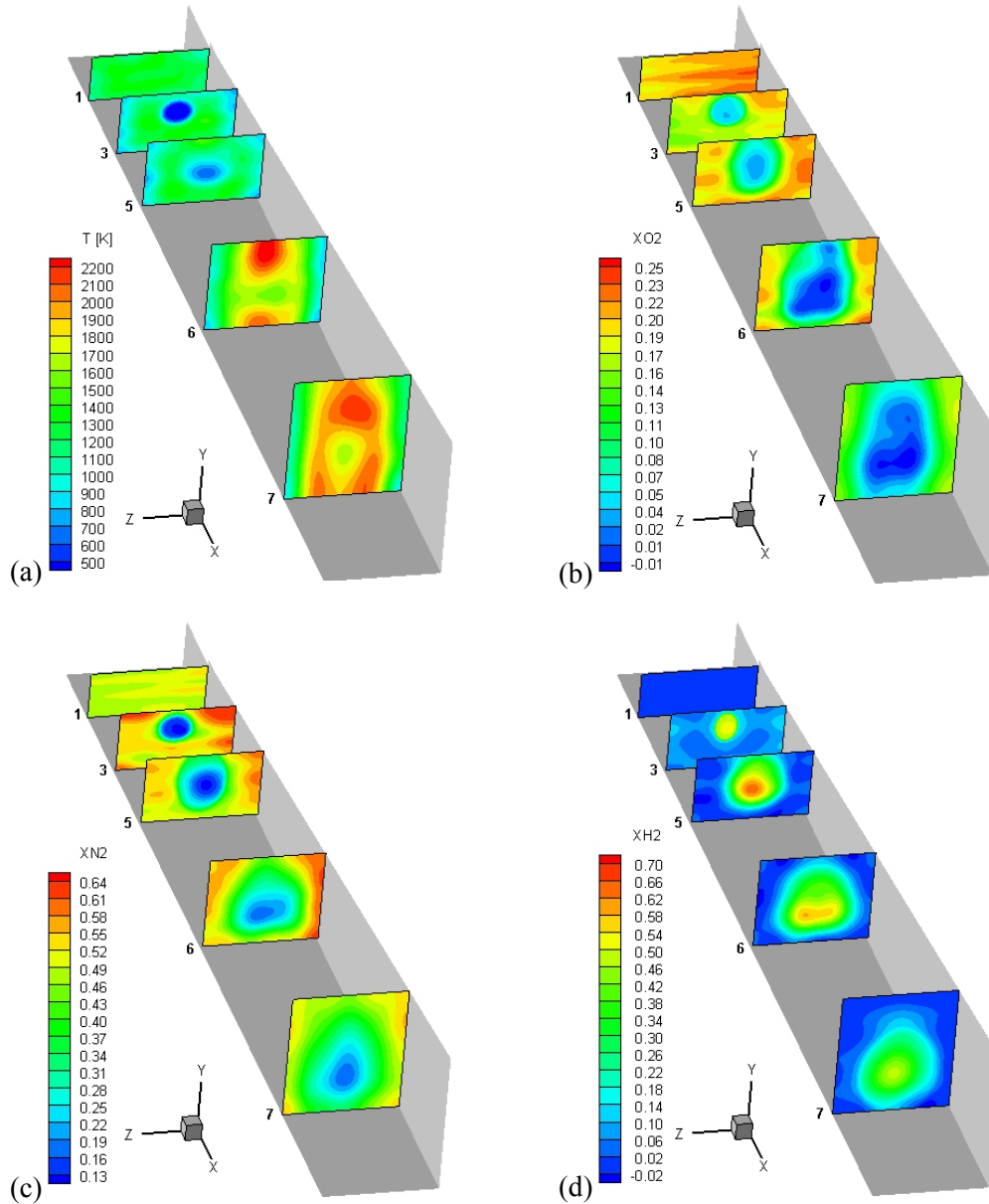


Figure 5: Maps of (a) mean temperature in Kelvin, (b) mean O_2 mole fraction, (c) mean N_2 mole fraction, (d) qualitative mean H_2 mole fraction at Mach 7 enthalpy for the vectored-fuel-injection case (Refs. 2 and 11).

3.1.2 Results of Supersonic Combustion Experiments

Figure 5 shows the results of the application of CARS to study supersonic combustion at NASA Langley Research Center. These images show a cut-away view of the 5 planes measured in the duct. Flow is from top left to bottom right. The fuel was injected from the top wall between planes 1 and 3. Temperatures are in Kelvin and species measurements are in mole fraction. While we believe that the temperature, N_2 and O_2 measurements are accurate, there is a known 10-15% systematic error in the H_2 measurements, so these should be considered qualitative. The maps show that the temperature of the gas entering the combustor was relatively uniform and close to the temperature predicted for these facility operating conditions. The N_2 and O_2 maps, on the other hand, show a left-to-right nonuniformity of the composition entering the combustor. In plane 3 the fuel jet appears in all four maps: the temperature, N_2 , and O_2 are low while the H_2 mole fraction is relatively high. In plane 5, the fuel jet has increased in size and has penetrated closer to the bottom wall. However the gas around the fuel jet has remained close to the inlet temperature. Significant combustion has occurred by plane 6, as evidenced by the increase in temperature and decrease in O_2 mole fraction. Combustion continues to occur at least until plane 7, where the temperature is still higher and O_2 mole fraction still lower. However, the H_2 maps show evidence of tens of percent of unburnt hydrogen in plane 7.

An interesting outcome of this experiment was the observation of delayed ignition: combustion appears to be inhibited until after plane 5. The test conditions were chosen based on CFD simulations that predicted stabilized combustion near the fuel injector, upstream of plane 3. Thus, the conditions of the experiment proved to be a very challenging case for comparison with CFD simulations. At present, 8 different research groups around the world have requested this data set for comparison with their CFD codes. The only CFD comparison with this data set published thus far [14] could not simultaneously reproduce measured wall-pressures, CARS-measured temperature maps and jet penetration visualizations provided by CARS. Varying parameters in the CFD simulation (such as freestream turbulence intensity, etc.) within reasonable limits produces results that agreed with one, but not all, of these different types of data. These results point to the fact that present CFD codes are not sophisticated enough to compute scramjet flowpaths accurately. Another conclusion is that comparisons between CFD and wall-pressures are not sufficient for gaining confidence in the ability of CFD to correctly predict flows: detailed flowfield data are also needed.

3.2 Liquid-Fueled Combustor Studies at Wright-Patterson Air Force Base, USA

3.2.1 Experimental Test Hardware and Procedure

The objectives of this investigation were to perform single-laser-shot measurements of temperature and mole-fraction ratios of CO_2/N_2 and O_2/N_2 under realistic non-sooting and sooting gas-turbine conditions. Measurements were performed in the exhaust stream of a liquid-fueled, swirl-stabilized CFM56 combustor for lean to rich overall equivalence ratios, ϕ , ranging from $\phi = 0.45$ to 1.0. A spatial traverse across the exhaust stream normal to the beam-propagation direction was performed to illustrate statistical differences between the relatively steady centerline and the turbulent shear layer. Temperature and mole-fraction histograms and scatter plots are used to distinguish the relative effect of fluid-dynamic fluctuations from that of random error.[7] The current work provides benchmark statistical distributions of temperature and mole-fraction ratios of CO_2/N_2 and O_2/N_2 in the exit plane of the combustor and is used to evaluate the effects of fuel composition and particulate-mitigating additives on flame chemistry. These measurements complement laser-induced incandescence (LII) and planar laser-induced fluorescence (PLIF) measurements of soot volume fraction and OH-radical mole fraction, respectively, which are ongoing in the current combustor.[15]

The atmospheric-pressure combustor facility employed in the current study has been described in detail

previously by Roy et al.[16] and Meyer et al.[15]. A brief overview is included here for reference. A single, JP-8-fueled pressure-swirl injector is center-mounted in a dual-radial air-swirling nozzle that feeds a 48-cm-long, 15.25-cm \times 15.25-cm square-cross-section flame tube, as shown in Figure 6. Changes in equivalence ratio, ϕ , from 0.45 to 1.0 are achieved by varying the pressure drop across the fuel-spray nozzle to obtain fuel mass flow rates of 0.9 to 1.9 g/s. The air-flow system consists of three Sierra 5600 SLPM mass flow controllers with $\pm 1\%$ full-scale accuracy. In the present investigation, air to the combustor was heated to 450 K, and the flow rate was held constant at ~ 0.0283 kg/s. The air-pressure drop across the combustor dome was $\sim 5\%$ of the main supply. The exhaust gases mix thoroughly and exit the combustor through a 43-cm long, tapered nozzle with an inner diameter of 4.8 cm at the exit plane. At high ϕ unburned fuel forms a diffusion flame at the exit of the exhaust nozzle; while it does not contribute to the CARS signal in the center of the nozzle, it does contribute to background flame emission. The entire combustor test stand is on an x-y-z translation system.

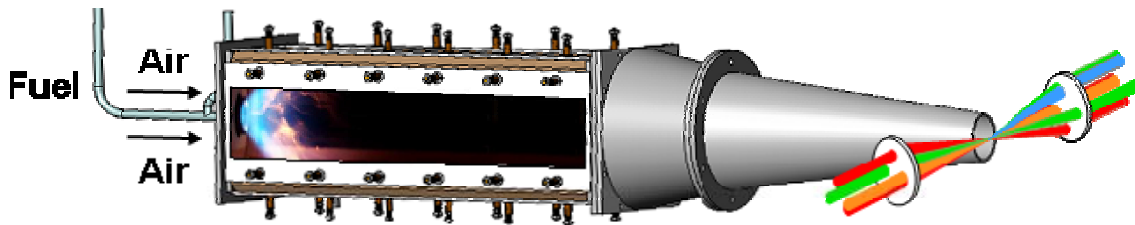


Figure 6: Cartoon schematic of the liquid-fueled, atmospheric-pressure CFM56 combustor rig employed in the combustion and fuel studies at Wright-Patterson Air Force Base described here. The beams from the DPDB-CARS system are represented as well.

3.2.2 Results of Liquid-Fueled Combustor Studies

Single-shot temperature and mole-fraction-ratio measurements of CO_2/N_2 and O_2/N_2 were performed in the exhaust stream of the JP-8-fueled, swirl-stabilized combustor over a wide range of equivalence ratios, ϕ , using the DPDB-CARS technique. As is evident in Figure 7(a), the measured temperatures (evaluated from the rovibrational N_2 spectra) are lower than the adiabatic flame temperatures by $\sim 20\%$ during lean combustor operation and by $\sim 25\%$ at the richest condition. The discrepancy between measured and calculated temperatures occurs primarily because data were collected ~ 0.9 m from the fuel nozzle and primary flame zone, leading to significant heat loss due to radiation and conduction. The increase in this discrepancy at higher ϕ is expected, therefore, because of increased heat transfer. Temperatures evaluated from the rovibrational and rotational spectra typically agree to within 40 K or 3%. This agreement confirms that the sub-equilibrium temperatures reported in Figure 7(a) are due to physical phenomena rather than experimental uncertainty, highlighting the utility of multi-pump CARS. The peak temperature difference is $\sim 5\%$ between the two techniques, which occurs at $\phi = 1.0$ when the pure rotational $\text{O}_2\text{-N}_2$ spectra have the lowest SNR.

The measured CO_2/N_2 mole-fraction ratios, shown in Figure 7(b), track equilibrium conditions to within 15% from $\phi = 0.45$ to 1.0, with better agreement near stoichiometric conditions where CO_2 mole fractions are higher. The O_2/N_2 mole-fraction ratios are also within 15% of equilibrium conditions up to $\phi = 0.7$ but are significantly below equilibrium at $\phi = 0.8$. It was not possible to extract the mole-fraction ratio of O_2/N_2 beyond $\phi = 0.8$ because of decreased mole-fraction levels and increased background interference.

Figures 7(c) and 7(d) show PDFs of temperature along the exhaust-nozzle centerline and in the outer shear

layer, respectively. The near-Gaussian PDF at the centerline is due to unbiased experimental error or random fluid-dynamic fluctuations. The bimodal PDF in the shear layer maintains a high-temperature peak equal to the centerline temperature, but also contains a low-temperature peak due to turbulent mixing with ambient air.

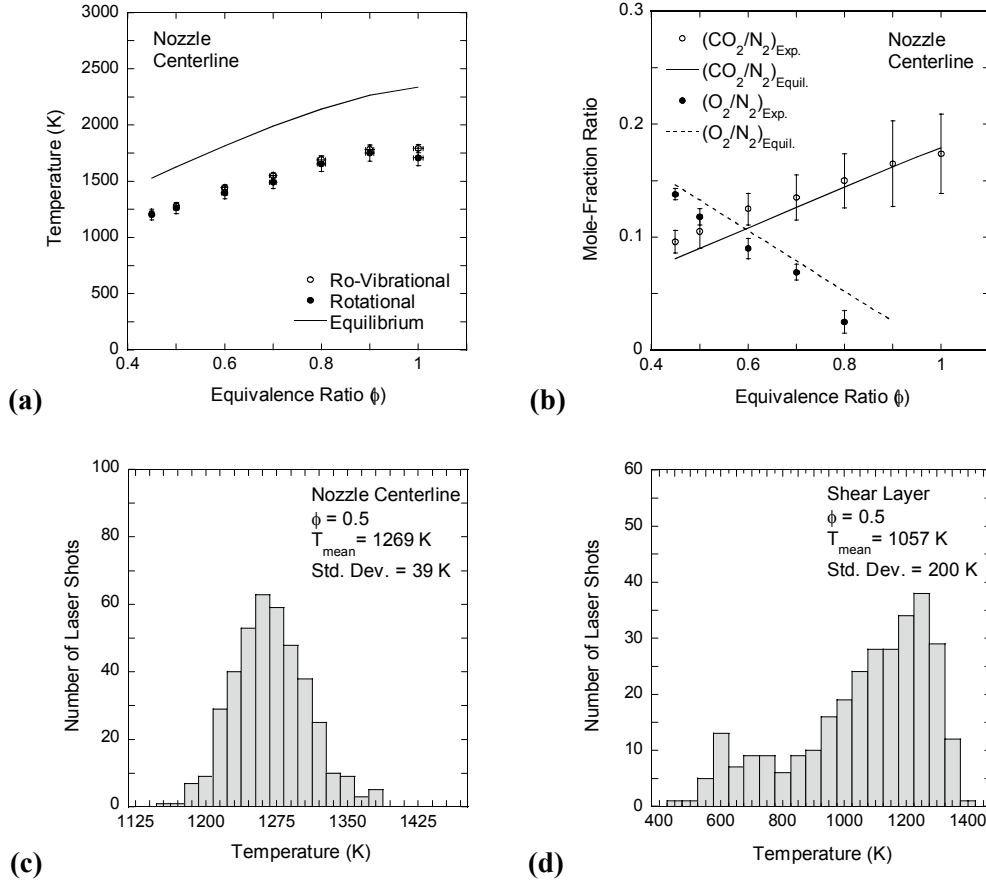


Figure 7: Comparison of experimental data with equilibrium calculations of (a) temperature and (b) mole-fraction ratios of CO_2/N_2 and O_2/N_2 acquired in the center of the combustor exhaust stream at various ϕ . PDFs of temperature collected at (c) exhaust centerline and (d) shear layer.

3.3 LOX/GH₂ Combustion experiment at ONERA, France

3.3.1 Experimental Test Hardware and Procedure

The MASCOTTE test facility was developed by ONERA to study elementary processes (atomization, droplet vaporization, turbulent combustion, etc.) that are involved in the combustion of cryogenic propellants.[17] The combustion chamber is equipped with a single-element injector fed by LOX and GH₂. The geometry of the injector element consists of a central tube of 5-mm inner diameter fed with LOX surrounded by a parallel annular duct of 12-mm diameter fed with gaseous hydrogen. Liquid oxygen is injected at a temperature of 85 K, while gaseous hydrogen is injected at room temperature. The combustion chamber is made of different interchangeable modules, which allows for the exploration of the whole combustion chamber by moving the visualization module to different longitudinal locations. Interchangeable nozzles are put at the exit of the

chamber and chosen according to the desired pressure level. The combustion chamber is designed with simplified thermomechanical models for 30 s of operation at atmospheric pressure, with a maximum mass flow rate of 120 g/s at a mixture ratio of 6. This test duration is reduced to 20 s at higher pressure.

As shown in Figure 3(d), temperature measurements from H_2 CARS spectra are obtained from the comparison of experimental spectra with theoretical ones using a simple least-squares fitting procedure. To obtain the best accuracy on temperature, the modeling of the spectral shape of Q-lines must predict the pressure broadening caused by collisional processes and Dicke narrowing [18]. This last phenomenon comes from the coupling between the Doppler effect and collisional processes as collision frequency increases, which is represented by the well-known Galatry model [19]. The complex Galatry function describes the observed spectra whatever the density. This property is important in CARS thermometry because the temperature being unknown, the density is unknown in the probe volume. The important parameter is then the collisional broadening, which depends on the density, the J quantum number, the temperature and the composition of the mixture. In our investigation, collisional linewidths were calculated using a methodology developed by Michaut et al. [20]. The same procedure of data reduction is used when H_2O is used as the probe molecule. For instance, Figure 3(e) shows a typical comparison of single-shot spectrum, consisting of H_2 and H_2O , recorded in the LOX/ GH_2 flame at 1.0 MPa.

3.3.2 Results from the ONERA MASCOTTE test facility

Temperature measurements using CARS on H_2 and H_2O in LOX/ GH_2 flames at pressures not exceeding 3.0 MPa have been already discussed by Grisch *et al.* [21]. To understand the physical mechanisms occurring in rocket engines, H_2 CARS thermometry was applied in supercritical regimes. The present section discusses selected data corresponding to high-pressure subcritical (3.0 MPa) and supercritical (6.5 MPa) flames. Figure 8 shows the radial mean temperature at various axial locations for 3.0 MPa and 6.5 MPa. The error bars represent rms fluctuations of measured temperatures. In the figures are also displayed the validation rate of measurements, defined as the ratio between the number of spectra successfully processed and the total number of laser shots during a run, which could range between 0 and 100% depending on the locations in the flame. Fluctuations of the validation rate can be attributed to different sources such as beam steering effects induced by large refractive index gradients, molecular composition into the probe volume and large signal fluctuations on the camera. At 3.0 MPa, only a few CARS signals are detected along the centerline at $X=50$ mm indicating that H_2 is rarely present in the LOX core, Figure 8(a). The mean temperature increases with radial distance reaching 1700 K at $Y=10$ mm. All these results suggest that combustion occurs in a layer bounding both propellants and that the flame can be seen as a thick shell surrounding the two fluids. Further downstream, progressive H_2 diffusion into the flow core occurs due to intense mixing and the validation rate improves, Figure 8(b). The mean temperature increases with distance from the injector, reaches 2100 K at $X=100$ mm and remains constant thereafter. Finally, whatever the location downstream from the injector, the H_2 radial temperature increases monotonically from the walls to the centerline, indicating a persistence of flow stratification at downstream sections. At supercritical pressures, the mean temperature profiles show different behavior, suggesting different types of fluid disintegration and flame structure. At $X=50$ mm (Figure 8(a)), it is interesting to note that 1) no CARS signal is detected on the centerline, 2) the maximum mean temperature (~ 900 K) is lower than that measured at 3.0 MPa, 3) the mean temperature decreases with increasing radial distance as opposed to the temperature profile recorded at subcritical conditions and 4) the rms fluctuations for each radial location are considerably reduced (< 200 K). All these effects suggest that the flame spreads in the immediate vicinity of the central core occupied by the dense stream of oxygen. The slight decrease of temperature with radial distance indicates that hot gases formed downstream recirculate in this region. The temperature standard deviation decreases with radial distance from 230 K at $Y=4$ mm to 100 K at $Y=16$ mm, whereas the validation rate increases from 0% at $Y=0$ mm to 70% at $Y=16$ mm, Figure 8(a). This

demonstrates that the recirculation zone is quite homogeneous. Lower mean temperatures than at 3.0 MPa (900 K vs. 1700 K) also suggest a different combustion regime as pressure increases from subcritical to supercritical conditions. Indeed, increasing pressure at subcritical conditions is known to enhance LOX atomization and vaporization leading to better mixing between GH_2 and LOX, thus faster burning and higher mean flame temperature over the radial section of the combustor. Shadowgraphy results also revealed that no ligaments and droplets were present around the LOX jet at supercritical conditions and that the flame took place in a thin mixing layer between GH_2 and LOX, hence leading to lower mean flame temperature due to a fluctuating thin reaction zone. Further downstream, the validation rate increases on the centerline, indicating that H_2 starts to be entrained and mixed with reactants and products within the inner jet flow, Figure 8(b).

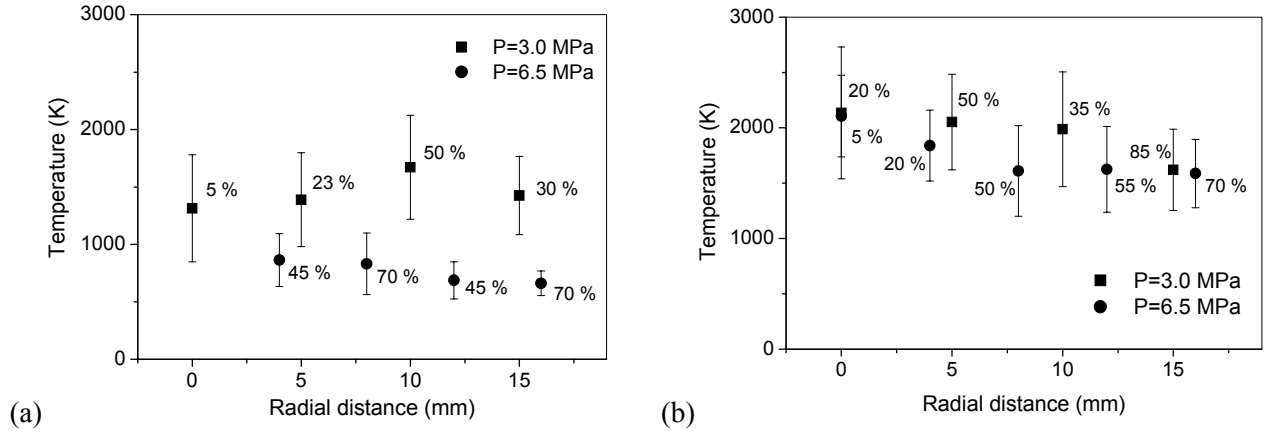


Figure 8: Radial profiles of mean and rms temperature fluctuations at two streamwise locations for P=3.0 MPa and P=6.5 MPa. (a) X=50 mm, (b) X=100 mm. Percentages indicate data validation rate.

Complementary measurements on the centerline at distances above 100 mm also indicated that this validation rate increases up to 70 % at larger locations for both pressure conditions. All these results confirm that the observed increase of the validation rate with axial distance along the centerline is related to the presence of a steep density gradient near the injector which progressively vanishes further downstream when mixing is achieved. On the centerline, the mean temperature reaches 2100 K, with larger rms fluctuations (400 K) due to intense turbulent fluctuations in the flow. Additional measurements at larger streamwise distances demonstrated that this maximum mean temperature becomes constant whatever the radial location. At these distances, maximum temperature rms fluctuations are around 600 K, which is comparable to those observed at 3.0 MPa.

Analysis of single-shot temperature measurements also allows calculation of individual temperature probability density functions (pdfs) within the flame region. For instance, Figure 9 displays pdfs recorded at 6.5 MPa. Each pdf is the result of the successfully processed data at a given location. At X=50 mm, the pdfs exhibit a well-defined bimodal structure for $4 \leq Y \leq 8$ mm, indicating intermittence due to large H_2 entrainment. The “cold” peak ranges between 600–700 K, which is due to the recirculation of hot gases formed downstream. The “hot” peak is observed in the 1300–1500 K domain, indicating that heat release from the combustion zone is less efficient than at subcritical conditions. Further downstream, the temperature pdfs are shifted towards the hot side with a maximum temperature lower than 1700 K. Similarly to subcritical conditions, the temperature pdfs also broaden with axial distance, which is characteristic of a thickening of the flame front.

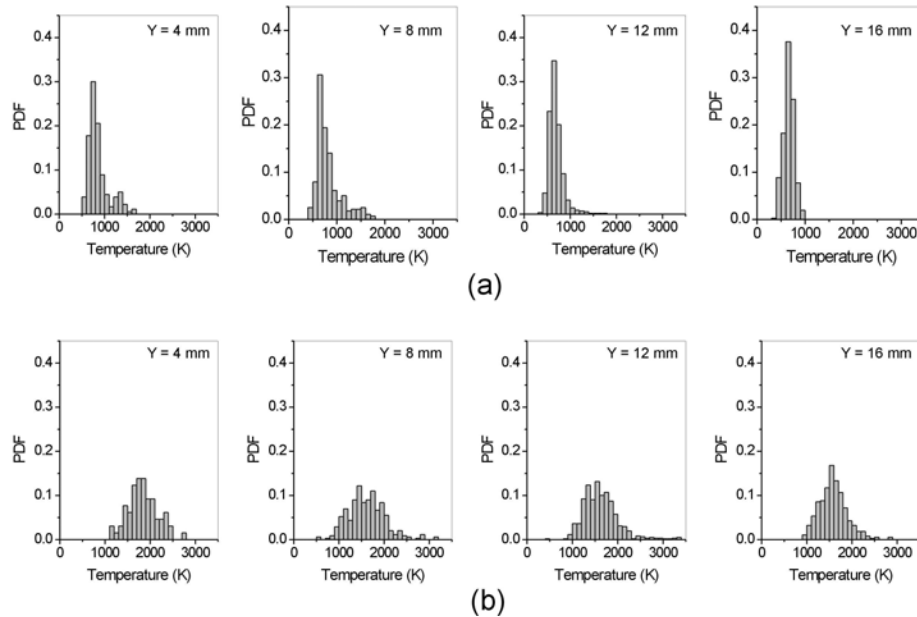


Figure 9: Temperature probability density functions from single-shot H₂ CARS spectra at two streamwise locations for P=6.5 MPa. (a) X=50 mm, (b) X=100 mm.

3.4 Diagnostics for Supercritical Combustion Investigations at DLR, Germany

3.4.1 Experimental Test Hardware and Procedure

The P8 test bench is a French/German high-pressure research and development facility located at the DLR Institute of Space Propulsion. The P8 facility is highly versatile and provides a broad range of operating conditions. Propellants supply systems (LOX, LH₂ and GH₂) can provide pressures up to 360 bar at the test bench interface to the test specimen. Mass flow rates can be controlled between 200 g/s and 8 kg/s for LOX, 50 g/s and 1.5 kg/s for GH₂, and 200 g/s and 3 kg/s for LH₂ respectively. The combustion chamber used for the experiments was developed by group of W.Mayer [22]. It has a single, shear coaxial injector element, the most common type used with LOX and H₂. Quartz glass windows provide the optical access necessary for the diagnostics. The windows are protected from thermal loads by hydrogen film cooling at ambient temperature. The film cooling does not influence the flow or combustion processes at the near injector region, which is the primary area of interest for the studies presented here. The combustion chamber has been operated at steady state, supercritical pressure conditions (~60 bar) for application of the diagnostic techniques. Tests have been done at two injection conditions, differing in the propellant injection temperatures. In condition 1, H₂ and O₂ had injection temperatures near 115 K, whereas in condition 2 H₂ and O₂ had temperatures near 60 K and 95 K respectively. The test duration was 20 seconds.

The laser system was set-up in a separate diagnostics room next to the test cell to reduce interference of combustion noise with the optical set-up and to minimise the risk for the expensive optical equipment in case of, for example, damage of the quartz windows. The beams entered the test cell through windows in the wall. They were focused in a planar BOXCARS arrangement, resulting in a probe volume length of 2 mm and a diameter of 0.1 mm. The detection system receives the CARS signal via a 6-m long 600- μ m-diameter fused silica fiber which transmits the CARS-signal to spectrograph in the diagnostics room. Adopting the optical

fiber avoids problematic issues arising from the large vibrations within the test cell. The repetition rate of the laser system was set at 10 Hz. The beam-guiding optics and focusing lenses mounted around the combustion chamber can be traversed along three axes to allow mapping of the flame. This translation stage was specifically designed and made of heavy-duty linear stages, welded steel brackets and optical rails.

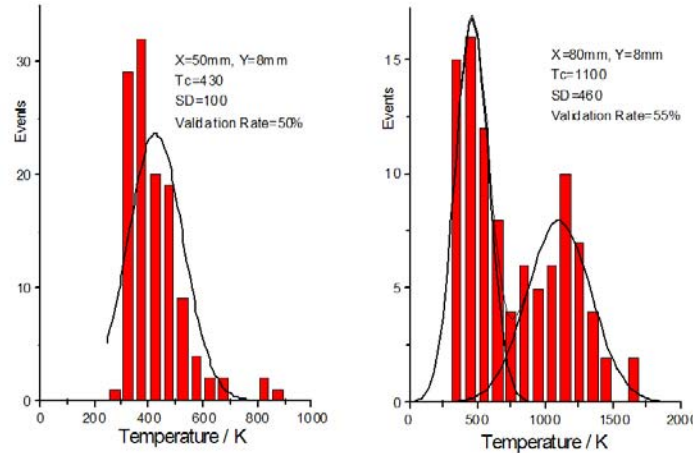


Figure 10: Temperature probability density functions from single-shot H₂ CARS spectra at two streamwise locations in the DLR combustor at (a) X=50 mm, (b) X=80 mm.

3.4.2 Results of supercritical combustion experiments at DLR

Experiments were performed at the two combustion chamber operating conditions with H₂-injection temperatures of 115 K at 65 K. Radial temperature profiles were measured at axial locations of 50 mm and 80 mm downstream of the fuel injector. With an H₂ injection temperature of 65 K, the fluid in the combustion chamber in the near-injector region appeared to be opaque and no light could be transmitted through the chamber volume, thus preventing the generation and detection of CARS-signals. Only for test conditions at H₂-injection temperatures of 115 K were CARS-signals were successfully obtained. In the near-injector region at an axial distance of 50 mm from the faceplate, data validation rates of up to 50% were achieved. At 80 mm downstream of the faceplate, validation rates of up to 70% were obtained. An example of the temperature histograms obtained at 80 mm downstream at a radial position of 6 mm and 8 mm is displayed in Figure 10. Bimodal structures can be observed in the histograms at measurement points for the 80 mm downstream cross-section. Figure 11 shows radial temperature profiles of CARS spectra for both cross-sections within the chamber. At the 50-mm downstream position, the data validation rate dropped near the chamber axis. For larger radial positions, temperatures near 400 K were measured. For all of the measurement points at the 80-mm axial position, two temperatures exist in accordance with the previously mentioned bimodal temperature histograms. The low temperature component is again near to 400 K, whereas in the high-temperature component a majority of the measured temperatures were below 1500 K at the combustion chamber cross-sections investigated. Due to the fact of low water concentration in the near-injector region and a strong presence of hydrogen lines in the spectral range of the expected water signal, only a few good H₂O-CARS water spectra were recorded. A systematic data evaluation of the water spectra could not be done based on the small number of data.

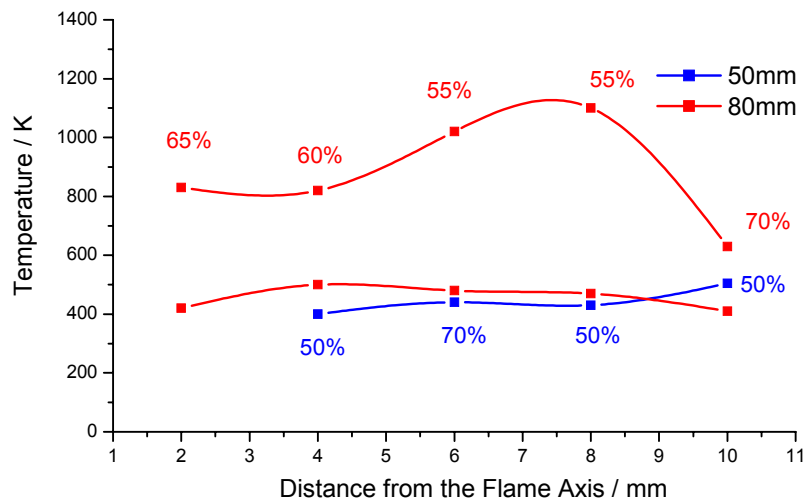


Figure 11: Radial temperature profiles in the DLR combustion chamber at (a) X=50 mm, (b) X=80 mm. Percentages indicate data validation rate.

4.0 CONCLUSION

This paper summarizes four different applications of the CARS measurement technique to practical aeronautics and aerospace propulsion systems. The four experiments used different approaches to measure the most relevant species in the combustor being investigated. In scramjet engines, N_2 , O_2 and H_2 are of interest and were probed by CARS at NASA Langley Research Center. In a liquid-hydrocarbon-fueled combustor for gas turbine engines, CO_2 and O_2 are of interest: their concentrations relative to N_2 were profiled at Wright-Patterson Air Force Base. Finally, in cryogenic LOX- H_2 rocket combustion chambers, H_2 and H_2O were probed at ONERA in France and DLR in Germany. All of these experiments mapped the temperature fields while some measured species mole fraction data as well. These data have several uses. First, they serve to explain how the combustors are operating. Mean temperature maps or profiles produced by CARS help visualize and describe the organization of the flow and to evaluate the extent of combustion. Probability density functions further show how mixing and combustion occur. Second, these data, including both mean measurements and pdfs, can be compared to CFD codes to test the codes. Such experimental results often show deficiencies in the models embedded in the codes and point to new theoretical models that should be developed. Finally, CARS data can be used to establish the coefficients in new theoretical models, such as turbulence or turbulence-chemistry interaction models. The improved CFD codes would then be used to design new combustors with higher fidelity than existing codes.

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